Development of a Transportable Gravity Gradiometer for Ground and Space Applications

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***Abstract*-- As part of NASA's Earth Science Technology Office Instrument Incubator Program, JPL is developing a transportable gravity gradiometer based on atom interferometer technology. This is an important developmental step towards a new space-borne gradiometer instrument, which can significantly contribute to global gravity mapping and monitoring which is important to the understanding of the solid earth, ice and oceans, and dynamic processes. In this paper, we will briefly review the principles and technical benefits of atom-wave interferometer-based inertial sensors in space. We will then describe the technical implementation of the transportable instrument and report its status.**

I. Introduction

The detection of the quantum interference of atomic states is a particularly versatile metrology tool, allowing precision measurements of a wide variety of physical phenomena. For the past sixty years, atomic clocks employing such quantum interference have evolved into remarkably precise laboratory instruments (keeping track of one second in a billion years), and have also been widely implemented in a variety of demanding real-world applications (GPS atomic clocks, for example, are capable of operating for years in a space environment). Over the past 15 years there has been great interest in using quantum interference to measure gravity, both in absolute terms, and in relative (gradient) measurements.

This technology is of particular importance to NASA for two reasons. First, gravity field mapping is one of the key measurements required in order to understand the solid earth, ice and oceans, and dynamic processes in a comprehensive model of our planet. There have been a number of gravity measurement missions, such as CHAMP [1] and GRACE [2], which measure gravity through the precise monitoring of the relative motion of satellites or onboard drag-free test masses. Other gravity missions using mechanical gravity gradiometers have also been planned or are under development [3,4]. Secondly, the microgravity environment of space promises a significant enhancement of the inertial sensing performance of an atom interferometer based on cold atoms.

In this paper we will discuss recent results obtained with a laboratory quantum gradiometer, in particular the measurements that we have made to facilitate the design of our next generation interferometer. We will also discuss the design and implementation of a next generation prototype being developed as part of the NASA's Instrument Incubator Program (IIP). This instrument will be capable of mounting on a mobile platform, so as to make measurements in remote locations. Building on extensive experience at JPL with atomic clock technology, we aim to produce a practical instrument that fully realizes the power of quantum interference to measure the local gravity field.

II. Principles of a Quantum Gradiometer

The development of atom interferometers using laser light pulses [5,6] has provided a sensitive new technique for inertial sensing. This technique employs laser-cooled atoms as identical drag-free test masses, unlike previous inertial sensors based on macroscopic test masses, and the de Broglie wave associated with each atom is then utilized to perform an interferometric measurement of the local acceleration. Light-pulse atom interferometers have already demonstrated impressive sensitivities in measurements of gravitational acceleration [7–9], rotations [9,10] and gravity gradients [11] in the laboratory.

The quantum gravity gradiometer in our laboratory employs two cold atom interferometers using laser-induced stimulated Raman transitions [6] to measure differential accelerations along the vertical direction.

The atom interferometers are realized by using a $\pi/2$–π–$\pi/2$ laser pulse sequence to drive velocity-sensitive stimulated Raman transitions between the two ground hyperfine states in cesium atoms in both interferometers. The counter-propagating Raman laser beams are oriented along the vertical launch axis, parallel to the direction of gravitational acceleration to be measured. The first $\pi/2$ pulse at time t_1 creates an equal superposition of atoms in the two hyperfine ground states. Only the excited state receives a photon recoil kick and therefore travels at a slightly different velocity, realizing a beam splitting analogous to that in a traditional Mach-Zehnder interferometer. Subsequent π and $\pi/2$ pulses at times $t_2 = t_1$+T and $t_3 = t_1 + 2T$, respectively, similarly redirect and recombine the atom waves to complete an interferometer loop, as illustrated in Fig. 2. The transition probability resulting from this interferometer sequence is given by $P = ½[1 - \cos(\Delta\phi)]$, where $\Delta\phi$ is the net phase difference between the two interferometer paths. This phase difference can be calculated from the Raman laser phases at the time and location of each interaction, *i.e.* $\Delta\phi = \phi(t_1, z_1) - 2\phi(t_2, z_2) + \phi(t_3, z_3)$. It can be further shown that the phase shift $\Delta\phi$ is related to the acceleration a according to $\Delta\phi = \mathbf{k}_{\text{eff}} \cdot \mathbf{a}T^2$, where T is the time between pulses and $\mathbf{k}_{\text{eff}} \equiv \mathbf{k_1}-\mathbf{k_2} \approx 2\mathbf{k_1}$ is the effective Raman laser wave number. The acceleration **a** is a vector sum of the gravitational acceleration g and platform acceleration a_p.

The atom interferometer phase shift can be measured by detecting the relative populations of the two hyperfine ground states via laser-induced fluorescence. The observed normalized signal takes the form of $P(\Delta\phi) = P_{\text{min}} + ½A[1 - \cos(\phi_0 + \Delta\phi)]$, where A is the normalized fringe amplitude $P_{max} - P_{min}$. To illustrate the sensitivity of a single such interferometer, consider a measurement with interrogation time $2T = 1$ s. As little as $3 \times 10^{-8}g$ of acceleration will cause a fringe phase shift of one full radian, and the acceleration measurement sensitivity will be determined by the SNR in the fringe measurement. A recent laboratory measurement demonstrated a sensitivity of $2 \times 10^{-8}g$ Hz$^{-1/2}$ and $1 \times 10^{-10}g$ resolution after two days integration [8].

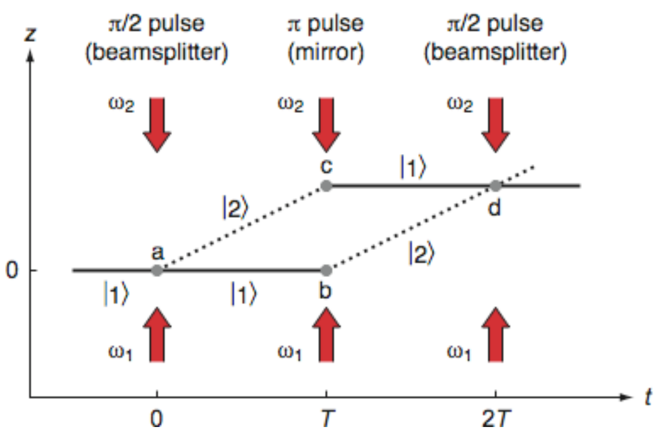

Fig. 1. Light-pulse atom interferometer diagram

Although the gravitational acceleration can be measured directly as described above, this measurement requires an inertial frame of reference (*i.e.* $a_p = 0$). This is a consequence of Einstein's Equivalence Principle: *i.e.* that an acceleration of the reference frame is indistinguishable from the gravitational acceleration in a local measurement. An inertial frame is difficult to realize, even in a laboratory environment. Gravity gradiometry thus provides a more fundamental measure of the gravitational fields by measuring the gravitational acceleration difference between two locations using a common reference frame so that other non-inertial accelerations are rejected as common-mode noise. In the quantum gravity gradiometer, the two acceleration measurements are performed simultaneously in two atom interferometers separated by a distance d by using the same Raman laser beams. Platform vibrations and laser fluctuations are effectively cancelled in the differential phase shift, so this measurement gives the gravitational acceleration difference in the two locations and the linear gravity gradient can be derived from the baseline distance d. With this configuration in a laboratory setting, a differential acceleration sensitivity of $4 \times 10^{-9}g$ Hz$^{-1/2}$ has been demonstrated with an effective common-mode rejection of 140 dB [11]. With the base line of 1.4 m used in our apparatus, this corresponds to a gravity gradient sensitivity of 34 E Hz$^{-1/2}$(1 E $\equiv 10^{-9}$ s^{-2}).

A. Microgravity operation

In general, precision measurements employing ultra-cold atoms are dramatically improved in microgravity due to the longer interaction times available. For the gradiometer this enhancement is much more profound, as the measurement sensitivity increases with the square of the interrogation time, in contrast to the linear dependence for Fourier-transform-limited measurements in atomic clocks. In a ground-based experiment in an atomic fountain, the interrogation time is limited to a fraction of a second due to practical limitations in the physical height of the apparatus. In a microgravity environment, interrogation times are limited only by the slow thermal expansion of the laser-cooled atoms. Such a benefit in microgravity environment has been recognized in other experiments with cold atom clocks [15,16]. Experiments using cold atom interferometers in space have also been proposed to test Einstein's general relativity as well as the Equivalence Principle [17].

III. LABORATORY DEVELOPMENT

A detailed description of our current prototype has been presented in [18]. Briefly, it consists of two separate vacuum chambers, each of which supports an atomic fountain. An ultra-cold (approximately 2μK) sample of approximately 10^8 Cesium atoms is prepared in each chamber using standard laser cooling techniques and then launched upwards to form an atomic fountain. A pair of diode lasers phase locked at an offset frequency of 9.2 GHz (the spacing between the two Cs ground hyperfine states) are used for the Raman manipulation of the atomic wavepackets. The stability of the phase lock reaches 6×10^{-13} at about 1 s and goes into the random walk regime at longer times.

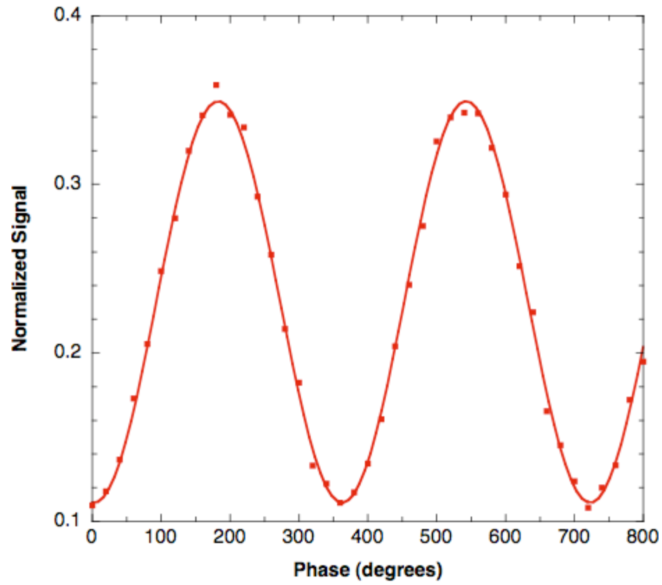

Fig. 2. Observed atom interferometer fringes. The phase of the final Raman $\pi/2$ pulse is scanned to generate characteristic interferometer fringe.

IV. Design Studies

A. Performance of the Laboratory Prototype

A careful evaluation of the performance of our laboratory prototype provides guidance for the design of the next generation instrument. A plot of the observed atom interferometer fringes is shown in Figure 2. We found it very difficult to evaluate the Stark shifts which arise because of different Raman laser intensities in the two chambers due to secondary reflections off of the windows in the beam path between the chambers. A straightforward improvement that will be implemented in the next generation instrument is to have the two interferometers connected in a single vacuum system. This also eliminates phase noise which arises due to turbulence in the air between the two chambers. Despite being unable to evaluate the systematic phase shifts, we can infer the system performance had we had two identical interferometers. With the demonstrated SNR of 200 and T = 100 ms, an acceleration measurement sensitivity of about $3 \times 10^{-9} g$ per measurement can be achieved. For our gradiometer separation of 1.4 m, we infer a gradiometer sensitivity of 34 E per measurement, or 34 E $\text{Hz}^{-1/2}$.

B. Phase feed-forward

One of the highest risks in developing a mobile gradiometer lies in adequately stabilizing the mirror that reflects the Raman laser beams against vibrations. Reducing this risk has been a high priority of our design studies. Our approach has been to implement a phase feed-forward scheme to detect vibrations and correct for them by adjusting the phase of the Raman beams. Such an approach can significantly reduce the amount of vibration isolation required. A sketch of our scheme is shown in Figure 3, an accelerometer mounted on the mirror platform detects vibrations and feeds a signal to a phase modulator which shifts the phase of the microwave reference signal for the Raman beam phase lock (this shifts the phase of one Raman beam relative to the other). We've demonstrated a greater than 70% reduction in atom interferometer phase noise due to spurious mechanical vibrations of Raman retro-mirror in our initial testing.

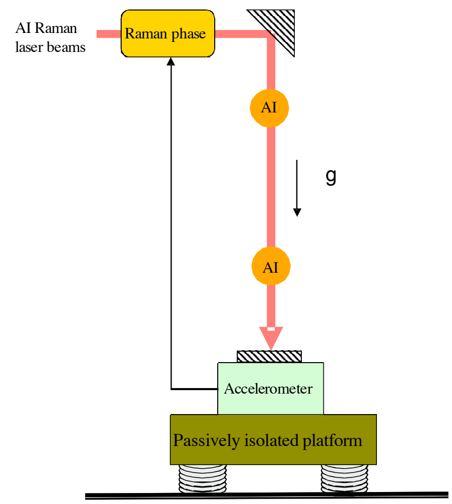

Fig. 3. Sketch of the phase feed-forward scheme

V. Transportable Prototype

Our next-generation gradiometer is being designed to be mounted on a moving platform, such as a small truck. While the instrument will not take data while the platform is in motion, it will be capable of operating in track after in field setup. This places significant additional design constraints in order to accommodate the requirements of size, weight, power consumption, and robustness. Additionally the instrument must be capable of stand-alone operation in a remote location. While this is still a terrestrial instrument, these developments will move the technology much further along the path to an eventual space-based application.

A. Atomic physics package

The mobile gradiometer will consist of two atom interferometer accelerometers housed in a single ultra-high vacuum (UHV) enclosure which is the core component of the atomic physics package. The interferometers are separated by 1 m in the vertical direction. Each accelerometer operates in an atomic fountain configuration. The UHV enclosure incorporates two titanium chambers with welded sapphire windows. The chambers are connected by a titanium tube, and the UHV is maintained by a getter pump located off of the middle of this tube, between the individual chambers. An additional ion pump is operated during the initial pump-down. During operation, its pump magnets are removed to minimize stray magnetic fields. Three layers of magnetic shield are incorporated to reduce stray magnetic fields both in the laser cooling region (to below 1 mG), and in the interaction region (on the order of μG). A dual-layer outer shield encloses both the MOT and interaction region, while a cylindrical inner shield surrounds the interaction region. Our finite element model shows that the total shielding expected will be $>10^4$ throughout the atomic fountain region.

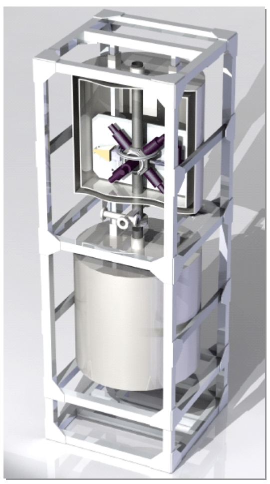

Fig. 4. Atomic Physics Package, showing magnetic shields on lower chamber, and a cutaway view on the upper chamber to reveal the optics and UHV chamber.

Fig. 5. A prototype of a slave module for the laser system. A total of 8 eight such modules will be incorporated into the laser design.

B. Laser system

The laser and optics system (LOS) provides laser power needed for two 2-D MOTs, two UHV MOTs, and the Raman beams (21 beams in total). The horizontal UHV MOT beams will additionally be used for detection and state selection. Our laser and optical system will feature an external cavity diode laser (ECDL) as master laser. An additional ECDL will be phase locked to the first. Manipulation of the reference frequency for this phase lock will provide the needed frequency agility required by the lasers for atom collection, sub-Doppler cooling, interferometry, and detection. Twelve injection locked slave diode lasers will be utilized. The system will deliver over 400 mW of output power incident on the atoms. It will be modular, and compact, fitting into a $40 \times 80 \times 12$ cm^3 volume. Fiber waveguides will couple the LOS to the physics package. Figure 5 shows a sample slave laser module. Eight such modules will be employed in our design, along with additional modules for the master, Raman, and repumper lasers.

C. Electronics and control

Operation of the gravity gradiometer requires precise control of all laser frequencies and amplitudes, the applied magnetic fields, as well as generation of precise timing sequences for the optical and microwave pulses. Stand-alone operation in the mobile instrument additionally requires that the control system be able to acquire and maintain the phase and frequency stabilization locks over a range of temperatures and environmental conditions. These tasks are performed by a combination of software and hardware.

The laser frequency offset and phase difference are precisely controlled by a homemade phase-lock loop (PLL). The microwave reference frequency for the PLL is generated by a custom-designed microwave synthesizer based on a 9.2 GHz dielectric resonant oscillator (DRO) mixed with the output of a 120 MHz direct-digital synthesizer (DDS) chip. The DDS provides the frequency agility required for all laser-atom interactions, including atom cooling and trapping, launching atoms as in an atomic fountain, and the stimulated Raman pulses required for atom interferometry. The DDS architecture allows these frequency and phase states to be updated using an "state trigger" pulse in order to synchronize this "state machine" operation to the experimental sequence.

Time-domain interferometry requires precise generation of the optical pulses that realize the atom interferometer. We employ a commercial multi-channel digital delay generator along with acousto-optic modulators (AOMs) to produce the laser pulse sequences with better than 1 ns timing resolution over the 0.5 s measurement cycle, and less than 100 ns rise time for the individual optical pulses. Additional analog waveforms for magnetic field and laser intensity control are generated by a computer with multi-channel digital-to-analog boards. The control computer also generates voltages for controlling the multiple slave laser currents and temperatures. We have demonstrated a robust algorithm for acquiring the phase and frequency stabilization locks, and the software is able to maintain the locks for the two master lasers and twelve injection-locked amplifier lasers indefinitely for autonomous operation.

VI. Conclusions

We are developing a transportable prototype of an atom interferometer-based gravity gradiometer that represents a major step towards a future microgravity based instrument. Building on decades of experience at JPL in designing atomic clocks for highly demanding space and ground applications, our aim is to bring this same quantum interference based technology to bear on the problem of gravity field mapping.

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